NASA TECHNICAL MEMORANDUM

NASA TM X-52902

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PERFORMANCE OF A SWIRL-CAN PRIMARY COMBUSTOR TO OUTLET TEMPERATURES OF 3600° F (2256 K)

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September 1970

This information is being published in preliminary form in order to expedite its early release.

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SUMMARY

A swirl-can full-annulus combustor was operated at an average outlet temperature of 3616 F (2264°K) which is only 337° R (187 K) below the stoichiometric temperature. The combustion efficiency, pattern factor, smoke emission, and pressure loss were all quite favorable. Additional work will be required before good durability and reliability are obtained.

INTRODUCTION

This report describes the results of the initial efforts to operate a full-annulus swirl-can primary combustor at outlet temperatures within a few hundred degrees of the stoichiometric temperature. Such a combustor may find application in future military aircraft wherein a minimum-size, minimum-weight turbine engine would be used for takeoff and acceleration to high cruise Mach numbers and a ram jet engine would be used for propulsion during cruise.

Swirl-can combustors have been investigated for many years at the NASA Lewis Research Center. The initial work in 1957 (references 1 and 2) was conducted with hydrogen fuel. Later work (references 3 and 4) was conducted to investigate the performance of this type combustor with vaporized hydrocarbon fuels. The more recent work in references 5 through 8 was conducted with liquid jet fuel and was devoted to improving the design of swirl-can combustors and extending their operating range to conditions typical of modern engines.

The most natural application of swirl-can combustors has always been deemed to be in engines requiring very high turbine-inlet temperatures. However, before undertaking the operation of a combustor at high temperatures, it was first necessary to obtain a satisfactory level of performance at lower temperatures. It was particularly important to obtain a reasonable temperature pattern factor at the turbine-inlet station. Inadequate mixing, as evidenced by poor pattern factors at the lower temperatures, would result in richer-than-stoichiometric regions (and, hence, low combustion efficiency and high pollutant emissions) as turbine-inlet temperatures approach the stoichiometric temperature. Therefore, it was only after completing the work described in references 1 through 8 that operation at near-stoichiometric temperatures was attempted.

COMBUSTOR DESIGN

The test combustor is shown in figures 1 and 2. It is an annular design which is 20.25 inches (0.514 m) long and 42 inches (1.067 m) in diameter. Its unique features include:

1. A combustor module array consisting of 120 modules, which distribute combustion uniformly across the annulus. All of the combustor airflow, exclusive of liner coolant flow, passes through the array providing an abundance of air for all stages of the combustion process.

2. A combustor module design, shown in figure 3, which performs several functions. Each module premixes fuel with air, swirls the mixture, stabilizes combustion in its wake, and provides large interfacial mixing areas between the bypass air through the array and the hot gases in the module wake.

3. A combustor liner design, the major portion of which is removed from the hot gas streamlines, thus requiring small amounts of coolant flow (approximately 4-7% of the total airflow). Simplified liner designs were utilized since diluent air is not injected through them.

INSTRUMENTATION

In excess of 400 pressures and temperatures were used to monitor combustor performance. Of particular note, a choked nozzle with a flow area of 132.50 square inches (0.0854 m^2) was used to determine combustor exit average temperatures and combustion efficiencies. The calculation of exit average temperature required inputs of total mass flow and pressure at the nozzle throat and the nozzle throat area. Circumferential traverses of a 5-radial-position probe were used to calibrate the choked nozzle under isothermal and burning conditions for exit temperatures up to 2300° F (1533 K). Calibrations were extrapolated to higher temperatures and defined a discharge coefficient of 0.985 and an area growth of 0.72 percent for each 1000° temperature rise.

TEST CONDITIONS

Test conditions were determined by fuel supply system capacity, which was approximately 3 lb/sec (1.36 kg/sec) or less, and by the choked nozzle throat area. The combustor inlet pressure ranged from 43.5 to 60 psia (30 to 41.4 n/cm^2); the inlet-air temperature was maintained at 600° F (589 K) by a heat exchanger in the inlet air piping. Reference velocities, which were limited by the choked nozzle area, varied from 130 ft/sec (39.6 m/sec) at isothermal conditions to 67 ft/sec (20.4 m/sec) at

3600° F (2256 K). All tests were conducted with ASTM-A1 liquid fuel.

TEST RESULTS

Combustor exit temperatures and combustion efficiency. - Figure 4 illustrates the rise in combustor exit temperature with increasing fuel-air ratio. Results indicate that nearly all of the data fall within a 2.5% span of 100% combustion efficiency. A one-percent deviation in the parameter $\frac{(\text{mass flow})}{(\text{nozzle area})\ (\text{total pressure})}$, which was used to calculate the exit gas temperature, produced approximately a 2.5% deviation in combustion efficiency. The highest combustion efficiency recorded occurred at a fuel-air ratio of 0.0301 and was 102.46%. If this efficiency were reduced to 100% by readjusting the nozzle area growth, and the remainder of the test data were normalized to this point, the maximum combustor exit temperature achieved would be reduced from 3616° to 3552° F (2264 to 2229 K).

Pressure loss. - Pressure losses for isothermal conditions and 600° F (589 K) inlet air temperature are shown in figure 5. For burning tests, combustor inlet Mach number decreased with increasing exit temperature due to the choked nozzle. Below is a compilation of pressure loss for various temperature ratios across the combustor and inlet Mach numbers.

Exit Temperature / Inlet Temperature Ratio °R/°R	Inlet Mach Number	Total Pressure Loss / Inlet Total Pressure %
2.0	.2784	4.9
2.5	.2450	4.2
3.0	.2251	3.8
3.5	.2093	3.5
3.85	.1967	3.3

Pattern factor. - The highest outlet temperature that was obtained, 3616° F (2264 K), is only 337° R (187 K) below the stoichiometric temperature. Consequently, the highest possible pattern factor at this condition was

$$\frac{337}{3616 - 600} = 0.112$$

where the pattern factor is defined as the maximum local exit temperature minus the average exit temperature divided by the temperature rise across the combustor.

Smoke and carbon formation. - The following smoke data were obtained:

Combustor Exit °F	Temperature K	Fuel-Air Ratio	Von Brand Smoke Number
1655 to 3054	1175 to 1952	.0173 to .0422	No detectable amount
3176	2020	.0447	5
3272	2073	.0467	6
3396	2142	.0497	9
3357	2121	.0495	10 - reduction in airflow
3423	2157	.0514	12
3485	2192	.0532	13
3540	2222	.0545	14
3616	2264	.0591	23.7

In addition, slight carbon deposits occurred on the center portion of about 1/3 of the swirlers.

Durability. - The combustor was operated continuously for a total of 3 hours and 46 minutes at exit temperatures above 3000° F (2122 K) and for 1 hour at exit temperatures above 3500° F (2200 K). Five single vanes from five different swirlers were damaged during this testing. An annular spacer ring, which sealed the downstream end of the outer liner and the combustor housing, was warped. A maximum liner temperature of 1680° F (1189 K) was recorded on the inner liner one inch (2.54 cm) downstream of the module array. No liner damage occurred.

Acoustic resonance. - Resonance or acoustic instability was not encountered during the tests.

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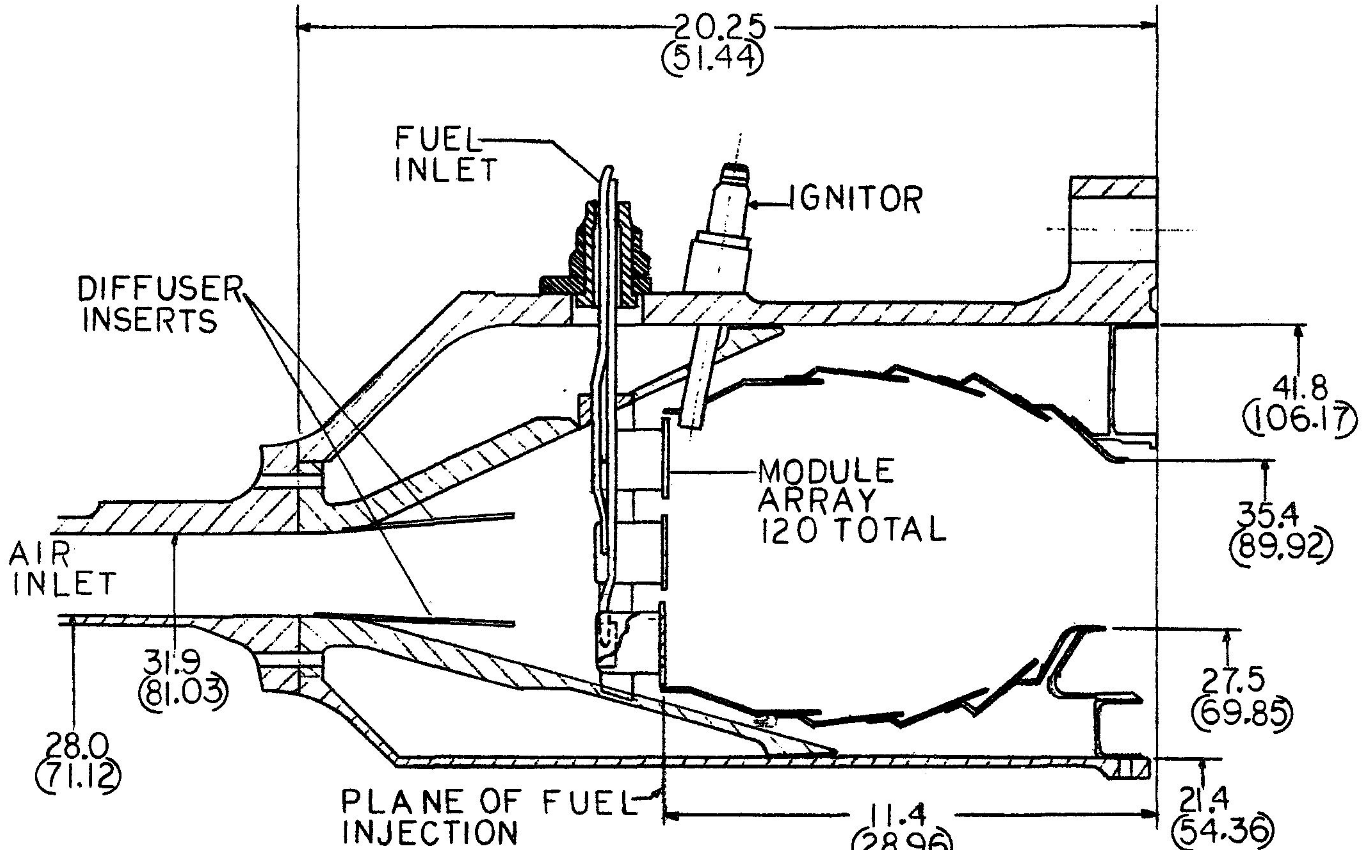
FIGURE I.
HIGH TEMPERATURE COMBUSTOR
FULL ANNULAR MODEL



DIMENSIONS IN INCHES (CM).

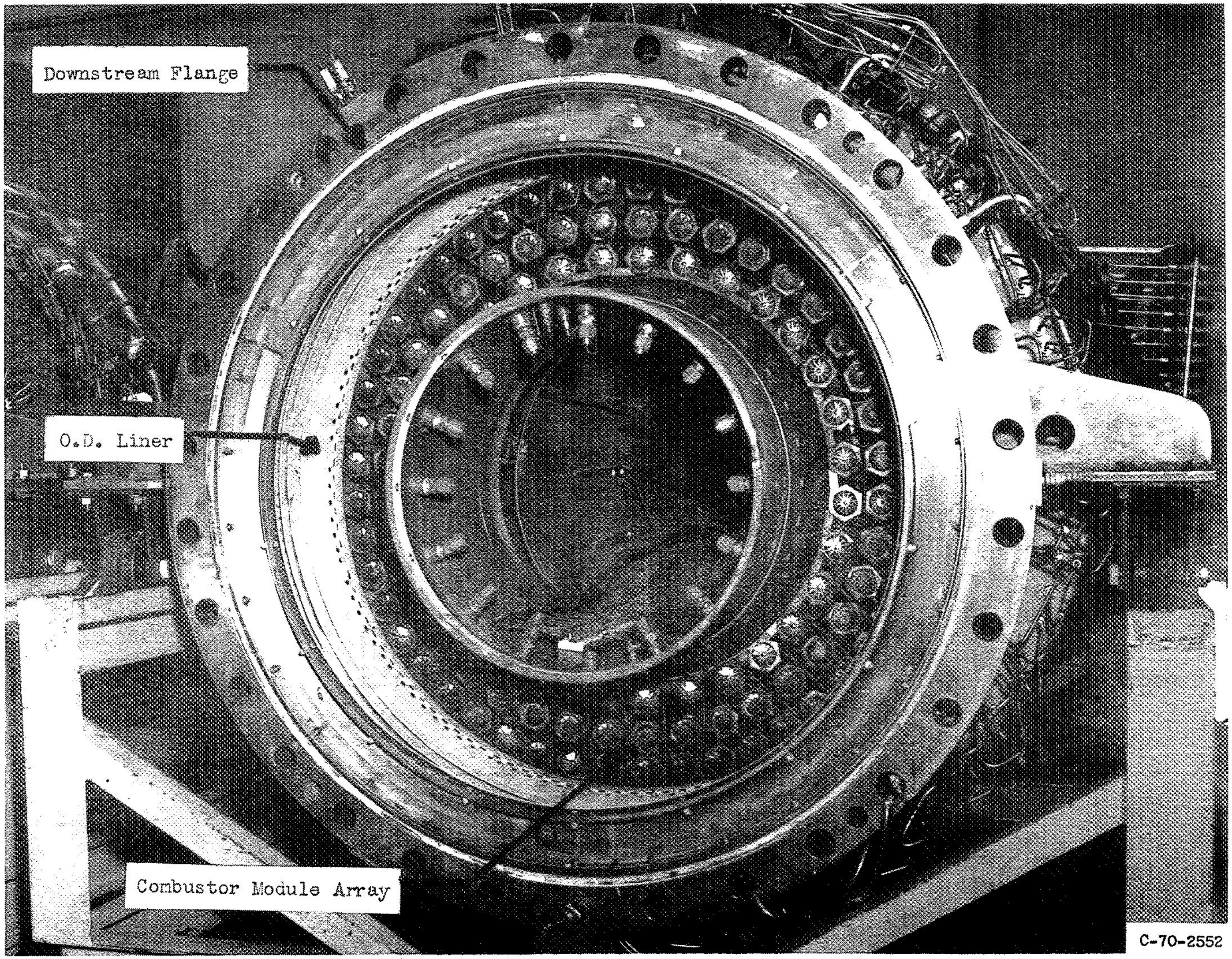
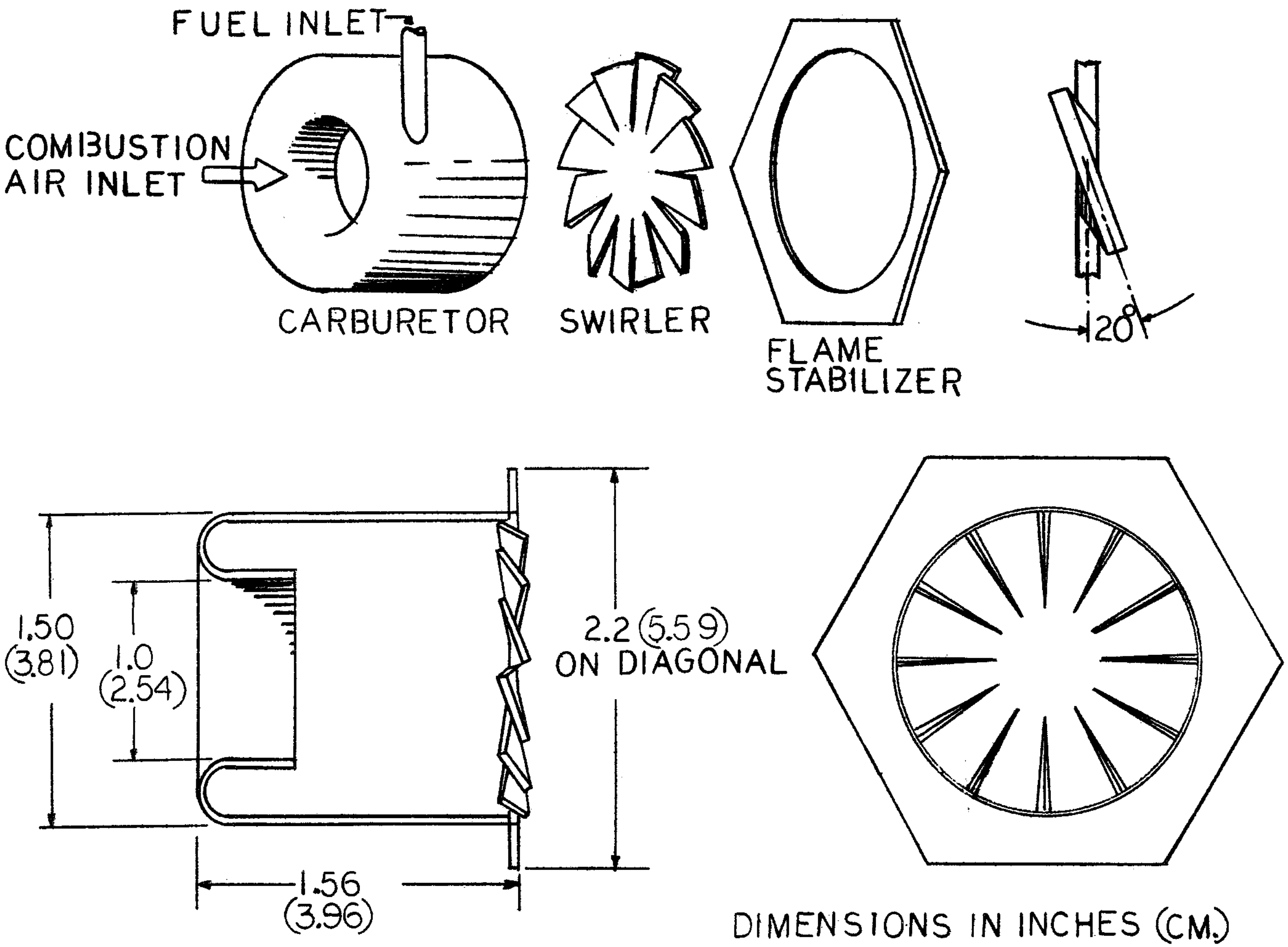


Figure 2.- Photograph of the combustor with the i.d. liner removed to better illustrate the combustor module array.

FIGURE 3.
COMBUSTOR MODULE DETAILS



DIMENSIONS IN INCHES (CM.)

Figure 4.- Combustor exit temperature and combustion efficiency as a function of fuel-air ratio. Combustor inlet air temperature, 600° F (589 K); airflow, 49-63 lb/sec (22.2-28.6 kg/sec); combustor inlet pressure, 43.5-60 psia (30-41.4 n/cm²)

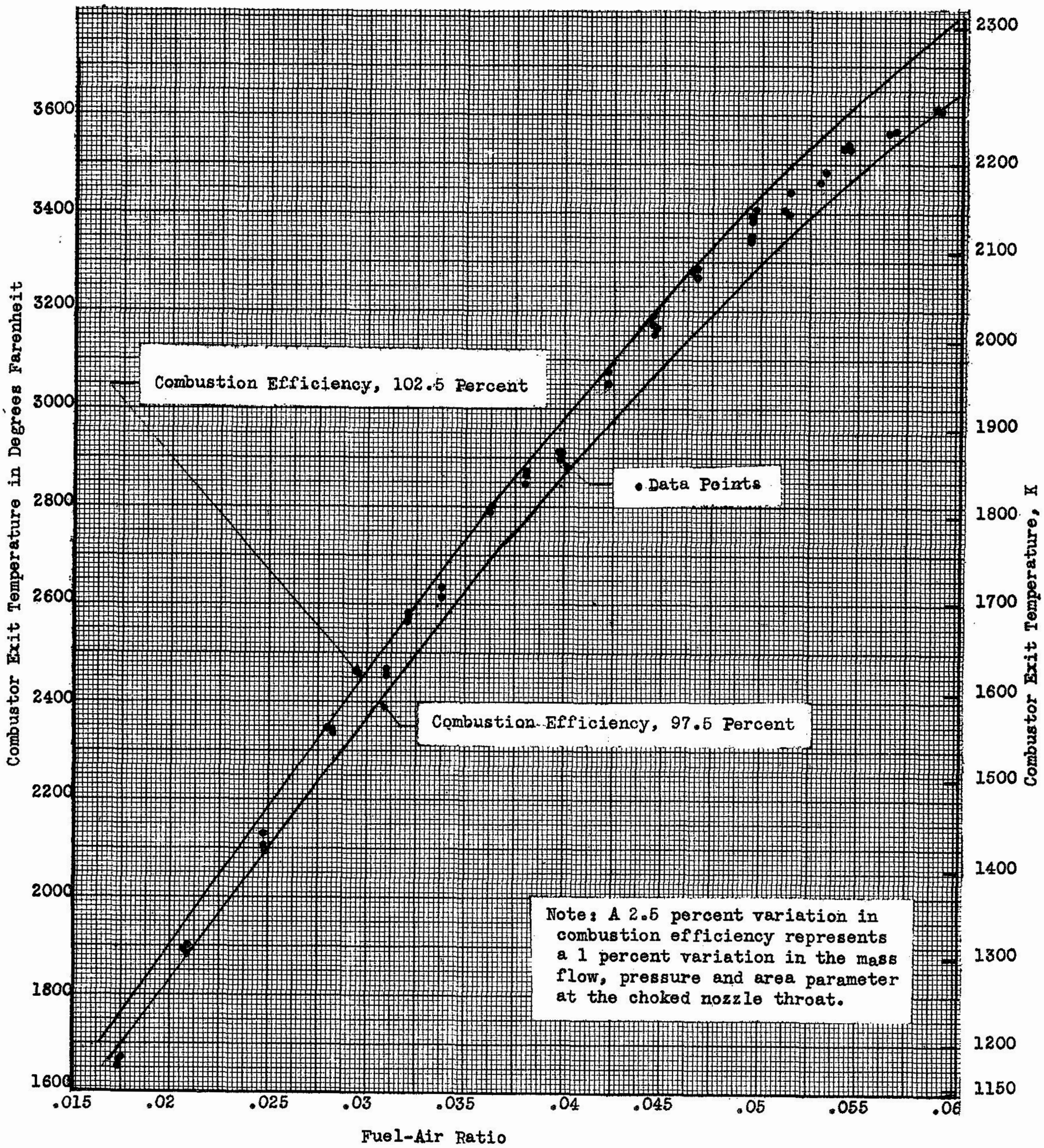


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Figure 5.- Effect of combustor inlet Mach number on pressure loss. Combustor inlet air temperature, 600° F (589 K).